

# Ambulatory Position and Orientation Tracking Fusing Magnetic and Inertial Sensing

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**Abstract**—This paper presents the design and testing of a portable magnetic system combined with miniature inertial sensors for ambulatory 6 degrees of freedom (DOF) human motion tracking. The magnetic system consists of three orthogonal coils, the source, fixed to the body and 3-D magnetic sensors, fixed to remote body segments, which measure the fields generated by the source. Based on the measured signals, a processor calculates the relative positions and orientations between source and sensor. Magnetic actuation requires a substantial amount of energy which limits the update rate with a set of batteries. Moreover, the magnetic field can easily be disturbed by ferromagnetic materials or other sources. Inertial sensors can be sampled at high rates, require only little energy and do not suffer from magnetic interferences. However, accelerometers and gyroscopes can only measure changes in position and orientation and suffer from integration drift. By combining measurements from both systems in a complementary Kalman filter structure, an optimal solution for position and orientation estimates is obtained. The magnetic system provides 6 DOF measurements at a relatively low update rate while the inertial sensors track the changes position and orientation in between the magnetic updates. The implemented system is tested against a lab-bound camera tracking system for several functional body movements. The accuracy was about 5 mm for position and 3 degrees for orientation measurements. Errors were higher during movements with high velocities due to relative movement between source and sensor within one cycle of magnetic actuation.

**Index Terms**—Accelerometer, gyroscope, Kalman filter, magnetometer, motion tracking, sensor fusion.

## I. INTRODUCTION

RECENT developments in miniature sensor technology have opened many possibilities for motion analysis outside the laboratory [3]. However, these ambulatory measurements do not yet provide full 6 degrees of freedom (DOF) information. Orientations of body segments can be estimated accurately by fusion of the signals from gyroscopes, accelerometers and magnetometers [7], [22]. By using the orientations of individual body segments, the knowledge about the segment lengths and joint characteristics, relative positions on the

body and angles between segments can be estimated [1], [16], [28]. In this kinematic chain, model and orientation errors of joints and segments can accumulate in position errors in the connecting body parts. Moreover, to track complex joints and nonrigid body parts like the back and shoulder accurately, more than three DOF, as given by an orientation measurement, are required. Position measurements on the body are important in many applications. For example, the distance between the center of mass and the position of the feet is necessary to evaluate balance in daily life. In virtual reality applications, the position of the arm with respect to the head mounted display should be known. Ergonomic studies would benefit from position measurements of the back to estimate its curvature to assess workload [2]. To get a better agreement between simulation results of a kinematic model and the measured data of a specific person, the model should be scaled to the geometry of that specific person [11].

Distances between body segments can principally not be assessed by numerical integration of the measured accelerations because of the unknown starting position. Only short-term estimates of position changes within seconds can be estimated due to the inherent integration drift. Giansanti *et al.* [9] used inertial sensors for accurate reconstruction of the movement of a body segment. However, these measurements were restricted to time-limited applications up to 4 s.

In this study, a portable magnetic system is designed and used to measure relative positions and orientations on the body. Magnetic trackers overcome line of sight restrictions related to optical and acoustic systems. The source is scaled and the system is designed to run on battery supply, making it suitable for body mounting and ambulatory measurements. The transmitter driver provides short current pulses in a sequence involving three coils having orthogonal axes. The three-axis magnetic sensor measures the strengths of each of the magnetic pulses that are related to the distance of the transmitter [12], [13]. Driving three orthogonal coils continuously requires a substantial amount of energy restricting the maximum measurement time and update rate with a set of batteries. Moreover, magnetic systems can be disturbed by ferromagnetic or other magnetic materials which will decrease their accuracy. The portable magnetic tracker is, therefore, combined with miniature inertial sensors. Accelerometers and gyroscopes measure fast changes in position and orientation, require less energy and are not sensitive for magnetic disturbances. The magnetic system is used as an aiding system and provides updates at a relatively low rate (1–2 Hz) to obtain long-term stable assessment of relative positions. Since the magnetic dipole source is only required to be active during a short period of time (several milliseconds per second), the average energy over time needed is limited. Measurements from

Manuscript received March 28, 2006; revised October 7, 2006. This work was supported by the Dutch Ministry of Economic Affairs under the FreeMotion project. Asterisk indicates corresponding author.

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Digital Object Identifier 10.1109/TBME.2006.889184

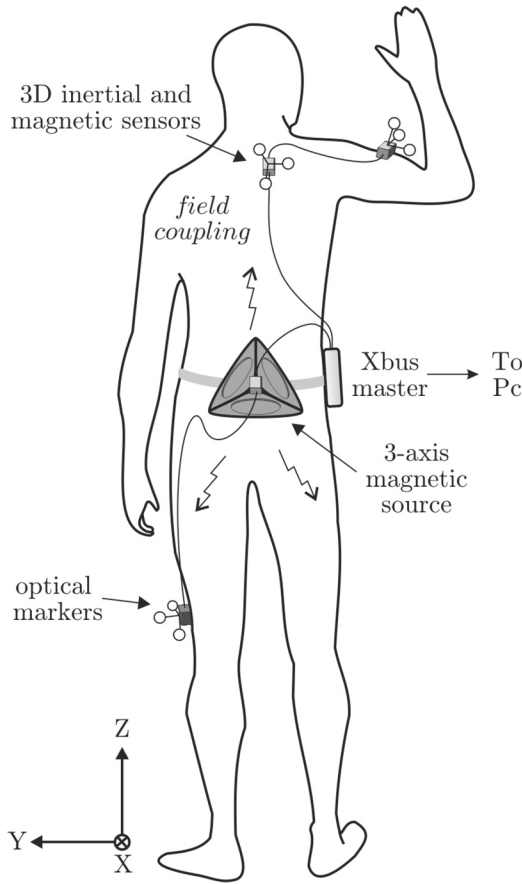


Fig. 1. Body-mounted magnetic system for measurement of relative distances and orientations on the body, consisting of a three-axis magnetic dipole-source worn by the subject and three-axis magnetic and inertial sensors on remote body segments. The sensors are connected by the Xbus system and transmitted by a wireless connection to a PC.

both sources and *a priori* knowledge about their behavior are combined using a complementary Kalman filter structure. The output of the filter is used to correct drift errors from the inertial sensors and reduce errors related to magnetic disturbances.

The objective of this study is to design and evaluate a new system for ambulatory measurements of position and orientation on the body. The major requirements for such a system are small weight and size, and no impediment of functional mobility. The fusion scheme of the portable magnetic tracker with inertial sensors is presented and the accuracy of the implemented combination of position and orientation estimates is evaluated by several experiments and compared with an optical reference system.

## II. SYSTEM DESIGN

### A. Magnetic Tracking

The magnetic tracker is comprised of three essential components [20]: 1) an actuator, consisting of three orthogonal coils, which are fixed to the body and generate magnetic fields; 2) 3-D magnetic sensors, fixed to several remote body segments, which measure the fields generated by the source; 3) a processor whose function is to calculate relative distances and orientations on the body using the actuator and sensor signals and to control the distributed magnetic actuation and sensing system (see Fig. 1).

Fig. 2 shows the timing relationship of two cycles between a 3-D orthogonal source and sensor. At time  $B_1$ , the  $X$ -source is activated, at  $B_2$ , the  $Y$ -source, and at  $B_3$ , the  $Z$ -source. At the end of a magnetic burst cycle, 9 values represent the relation in 6 DOF between source and sensor; three sensor values for each of the three transmitting coils. The equations presented by Kuipers [14] are used to calculate the 6 DOF. The three position coordinates are expressed in the magnetic frame ( $M$ ) by  ${}^M\mathbf{q}'$ . The relative orientation between source and sensor is expressed by rotation matrix  ${}^M\Psi'$ .

### B. Inertial Tracking

Rate gyroscopes measure angular velocity  $\boldsymbol{\omega}$ , and if integrated over time, provide the change in angle (or orientation) with respect to an initially known angle [4]

$${}^{GS}\dot{\boldsymbol{\Theta}}_t = {}^{GS}\boldsymbol{\Theta}_t[\boldsymbol{\omega}_t \times] \quad (1)$$

where  ${}^{GS}\boldsymbol{\Theta}_t$  is the rotation matrix describing the transformation from sensor to global frame at time  $t$ . Linear accelerometers measure the vector of acceleration  $\mathbf{a}$  and gravitational acceleration  $\mathbf{g}$  in sensor coordinates ( $S$ ). The sensor signals can be expressed in the global reference system ( $G$ ) if the orientation of the sensor  ${}^{GS}\boldsymbol{\Theta}_t$  is known

$${}^G\mathbf{a}_t - {}^G\mathbf{g} = {}^{GS}\boldsymbol{\Theta}_t ({}^S\mathbf{a}_t - {}^S\mathbf{g}). \quad (2)$$

After removing the gravity component, the acceleration  $\mathbf{a}_t$  can be integrated once to velocity  $\mathbf{v}_t$  and twice to position  $\mathbf{p}_t$ , all in the global frame

$$\mathbf{v}_t = \mathbf{v}_0 + \int_{t_0}^t \mathbf{a}(\tau) d\tau \quad (3)$$

$$\mathbf{p}_t = \mathbf{p}_0 + \int_{t_0}^t \mathbf{v}(\tau) d\tau \quad (4)$$

where the initial velocity  $\mathbf{v}_0$  and position  $\mathbf{p}_0$  should be known.

### C. Sensor Fusion

Fusing an inertial navigation system as described above, with other systems is well established in traditional navigation applications [5]. To blend the available data from the inertial sensors and magnetic system efficiently, a complementary Kalman filter has been designed (see Fig. 3). The inertial measurement unit provides output at a rate of 120 Hz. These measurements of angular velocity  $\boldsymbol{\omega}$  and acceleration  ${}^S(\mathbf{a} - \mathbf{g})$  are used to track the changes in position  $\mathbf{p}^-$  and orientation  $\boldsymbol{\Theta}^-$  using the inertial navigation equations [(1)–(4)]. In traditional navigation, this is often referred to as dead reckoning. These estimates are denoted by a minus superscript. A plus superscript denotes the solution that is made after correction by the Kalman filter. The magnetic tracker provides updates at a rate of 1.67 Hz. When a magnetic position and orientation solution has become available after a series of three pulses, this output is compared with the estimates of the inertial navigation system. The difference

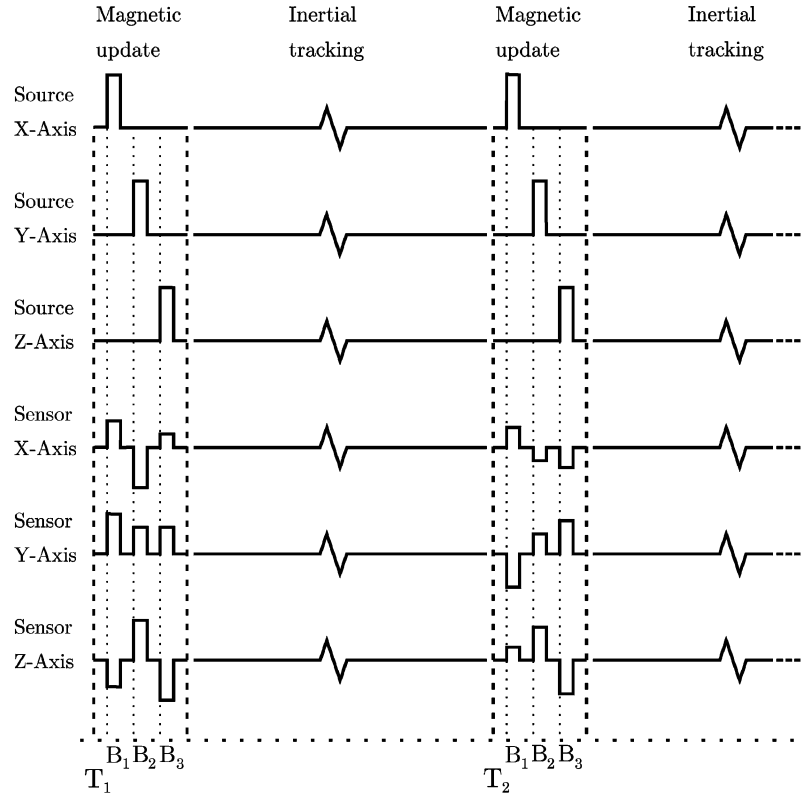


Fig. 2. Timing diagram of magnetic and inertial sensor fusion. During  $B_1$ – $B_3$ , three magnetic pulses are generated from which 6 DOF can be calculated. In between magnetic measurements, inertial sensors are used to track changes in position and orientation. In the experiments,  $B_1$ – $B_3$  was 60 ms, and  $T_1$ – $T_2$  600 ms.

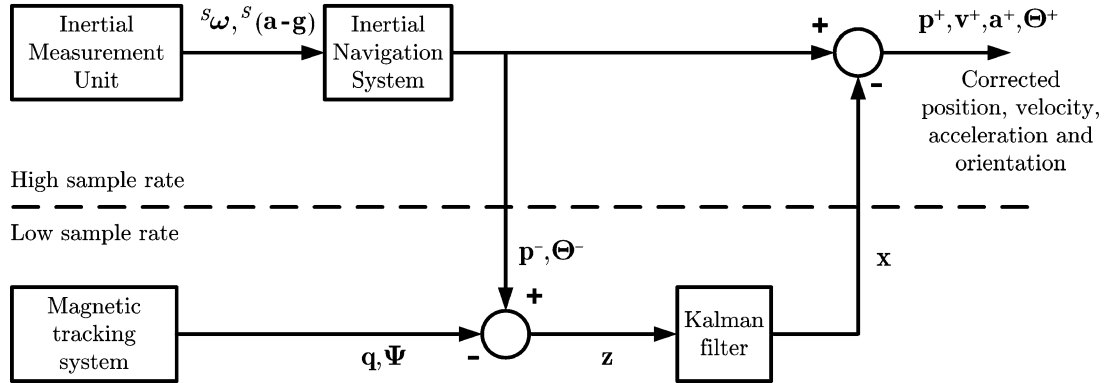


Fig. 3. Complementary Kalman filter structure for combining inertial and magnetic measurements. Position  $\mathbf{p}^-$  and orientation  $\Theta^-$  are estimated at a high sampling rate, using the inertial navigation equations [(1)–(4)], denoted by the minus superscript. At a lower rate, the magnetic system provides updates  $\mathbf{q}$  and  $\Psi$ . The differences between the two systems  $\mathbf{z}$  is delivered to the Kalman filter which estimates the errors in the quantities of interest  $\mathbf{x}$ . These are used to correct position, velocity, acceleration, and orientation estimates resulting in  $\mathbf{p}^+$ ,  $\mathbf{v}^+$ ,  $\mathbf{a}^+$ , and  $\Theta^+$ , denoted by a plus superscript.

between the inertial and magnetic system in position and orientation is the measurement update  $\mathbf{z}$  for the Kalman filter. The Kalman filter processes the measurements to deduce a minimum error estimate of the states  $\mathbf{x}$  which are used to correct the inertial system. It uses a state space representation to model the relation between errors in estimated state variables and the measured errors.

This relation is described by a discrete time error signal model, operating at the sample rate of inertial sensors

$$\mathbf{x}_{\varepsilon,t+1} = \mathbf{A}\mathbf{x}_{\varepsilon,t} + \mathbf{w}_t \quad (5)$$

where  $\mathbf{A}$  is the state propagation matrix from time  $t$  to  $t + 1$ . When a magnetic measurement comes available, the linear measurement equation for the data fusion Kalman filter can be represented by

$$\mathbf{z}_{\varepsilon,t} = \mathbf{C}\mathbf{x}_{\varepsilon,t} + \mathbf{v}_t \quad (6)$$

where  $\mathbf{w}_t$  and  $\mathbf{v}_t$  represent process and measurement noise with covariance matrices  $E[\mathbf{w}_t\mathbf{w}_t^T] = \mathbf{Q}_t$  and  $E[\mathbf{v}_t\mathbf{v}_t^T] = \mathbf{R}_t$ , respectively. The  $\mathbf{C}$  matrix describes the relation between the states and the measurements (Kalman filter input). The Kalman filter equations can be found many textbooks (e.g., [5] and [8]).

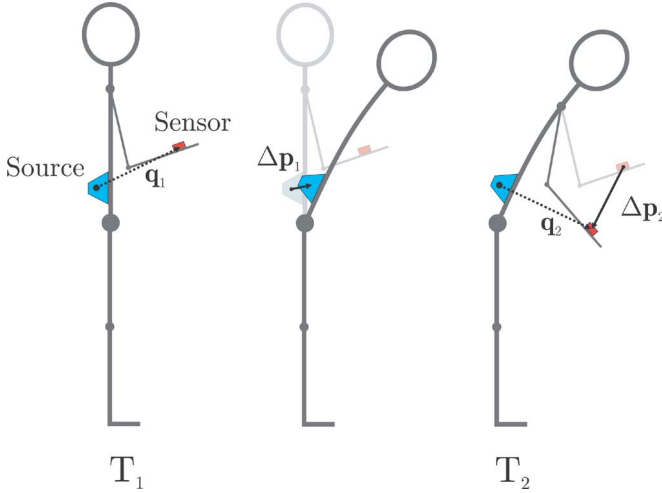


Fig. 4. Relative coupling between source and sensor. The source is placed on the back of the subject, the sensor on the wrist. At  $T_1$ ,  $q_1$  is determined by the magnetic system. Then, the source on the back is moved by  $\Delta p_1$ , and simultaneously, the sensor on the arm is moved over a distance  $\Delta p_2$ . At  $T_2$ , the magnetic system provides an update of the position  $q_2$ .

The outputs of the filter are used to correct the position, velocity, acceleration, and orientation estimates resulting in  $\mathbf{p}^+$ ,  $\mathbf{v}^+$ ,  $\mathbf{a}^+$ , and  $\boldsymbol{\Theta}^+$ . The  $\mathbf{A}$  and  $\mathbf{C}$  matrix and the covariances matrices are determined in Section II-D.

The magnetic system outputs 6 DOF of the sensor with respect to the position and orientation of the source. Since the source can move, no absolute position and orientation is given by this system. To estimate the orientation of the source  ${}^{GM}\boldsymbol{\Phi}$ , an inertial and magnetic sensor was attached to the source. The accelerometers provide a measure for inclination, the magnetometers are used as a compass to provide a reference in the horizontal plane and the gyroscopes measure fast changes in orientation by integrating angular velocities [22]. The position coordinates of the magnetic frame are aligned with the axes of the global frame, with the origin being the center of the source by using

$${}^G\mathbf{q}_t = {}^{GM}\boldsymbol{\Phi}_t^M \mathbf{q}_t'. \quad (7)$$

Similar, to express the orientation of the sensor  ${}^M\boldsymbol{\Psi}'$ , measured by the magnetic system, in the global frame, it should be multiplied by  ${}^{GM}\boldsymbol{\Phi}$  resulting in the orientation  ${}^G\boldsymbol{\Psi}$ .

Fig. 4 shows an example of the coupling between a moving sensor module and a moving source. At  $T_1$  the magnetic system emits its sequence of three pulses, and the distance  $q_1$  between source and sensor can be determined. Then, the source on the back is moved by  $\Delta p_1$ , and simultaneously, the sensor on the arm is moved over a distance  $\Delta p_2$ . At  $T_2$ , the magnetic system provides an update of the position  $q_2$ , which can be compared in the Kalman filter with the position estimate  $\mathbf{p}$ , by integrating of  $\mathbf{a}_{\text{net},t}$ . The resulting net position change between source and sensor depends on the measured accelerations of the sensor and source in the global frame

$$\mathbf{a}_{\text{net},t} = \mathbf{a}_{\text{sensor},t} - \mathbf{a}_{\text{source},t}. \quad (8)$$

#### D. Error Models

The fusion filter states consists of 21 error states for the position  $\mathbf{p}_\varepsilon$ , velocity  $\mathbf{v}_\varepsilon$ , orientation  $\boldsymbol{\Theta}_\varepsilon$ , accelerometer bias  $\mathbf{a}_\varepsilon$ , gyroscope bias  $\boldsymbol{\omega}_\varepsilon$ , magnetic position error  $\mathbf{q}_\varepsilon$ , and magnetic orientation error  $\boldsymbol{\Psi}_\varepsilon$ , all in the three directions

$$\mathbf{x}_{\varepsilon,t} = [\mathbf{p}_{\varepsilon,t}, \mathbf{v}_{\varepsilon,t}, \boldsymbol{\Theta}_{\varepsilon,t}, \mathbf{a}_{\varepsilon,t}, \boldsymbol{\omega}_{\varepsilon,t}, \mathbf{q}_{\varepsilon,t}, \boldsymbol{\Psi}_{\varepsilon,t}]^T. \quad (9)$$

The discrete inertial error model with timestep  $\Delta t$ , follows directly from (1) to (4). The position error is calculated by the integration of the velocity error

$$\mathbf{p}_{\varepsilon,t+1} = \mathbf{p}_{\varepsilon,t} + \Delta t \mathbf{v}_{\varepsilon,t}. \quad (10)$$

The velocity error is the integration of the acceleration error and the orientation error multiplied by the measured acceleration signal

$$\mathbf{v}_{\varepsilon,t+1} = \mathbf{v}_{\varepsilon,t} + \Delta t ({}^G(\mathbf{a}_t - \mathbf{g}) \times \boldsymbol{\Theta}_{\varepsilon,t} + \mathbf{a}_{\varepsilon,t}). \quad (11)$$

The orientation error can be found by taking the first-order approximation of the strapdown integration step

$$\boldsymbol{\Theta}_{\varepsilon,t+1} = \boldsymbol{\Theta}_{\varepsilon,t} + \Delta t [\boldsymbol{\omega}_{\varepsilon,t} \times]. \quad (12)$$

The acceleration and angular velocity errors  $\mathbf{a}_{\varepsilon,t}$  and  $\boldsymbol{\omega}_{\varepsilon,t}$  are modeled as first order Markov processes

$$\mathbf{a}_{\varepsilon,t+1} = \mathbf{a}_{\varepsilon,t} e^{-\beta_a \Delta t} \quad (13)$$

$$\boldsymbol{\omega}_{\varepsilon,t+1} = \boldsymbol{\omega}_{\varepsilon,t} e^{-\beta_\omega \Delta t}. \quad (14)$$

The correlation between successive samples from magnetic position and orientation measurements is zero

$$\mathbf{q}_{\varepsilon,t+1} = \mathbf{0} \quad (15)$$

$$\boldsymbol{\Psi}_{\varepsilon,t+1} = \mathbf{0}. \quad (16)$$

The state transition matrix  $\mathbf{A}_t$  is defined from (10)–(16) as

$$\mathbf{A}_t = \begin{bmatrix} \mathbf{I}_3 & \Delta t \mathbf{I}_3 & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{I}_3 & \Delta t [(\mathbf{a} - \mathbf{g}) \times] & \Delta t \mathbf{I}_3 & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{I}_3 & \mathbf{0} & [\Delta t \times] & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & e^{-\beta_a \Delta t} \mathbf{I}_3 & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & e^{-\beta_\omega \Delta t} \mathbf{I}_3 & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \end{bmatrix} \quad (17)$$

where  $\mathbf{I}_3$  is a  $3 \times 3$  identity matrix and  $\mathbf{0}$  a  $3 \times 3$  matrix of zeros. It is assumed that the noise for each state variable is uncorrelated with the noise for each other state. Hence, all nondiagonal terms of the noise matrix  $\mathbf{Q}_t$  matrix are zero and the diagonal terms are simply the variances of the random variables.

### E. Measurement Model

The first measurement presented to the Kalman filter is the position measured by the magnetic system  $\mathbf{q}_t$  minus the inertial position estimate  $\mathbf{p}_t$ . For the orientation correction, there are several alternatives to combine the inertial and magnetic measurements.

- 1) Compare orientation  $\Theta_t$  with magnetic orientation estimates expressed in the global frame  $\Psi_t$ . The discrete measurement model is formed from the inertial position error  $\mathbf{p}_{\varepsilon,t}$  and magnetic position error  $\mathbf{q}_{\varepsilon,t}$ , and the elements of the inertial orientation error  $\Theta_{\varepsilon,t}$  and magnetic orientation error  $\Psi_{\varepsilon,t}$

$$\mathbf{C}_t = \begin{bmatrix} \mathbf{I}_3 & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{I}_3 & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{I}_3 & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{I}_3 \end{bmatrix}. \quad (18)$$

- 2) Compare orientation  $\Theta_t$  with the orientation  $\Xi_t$  obtained by fusing the accelerometer, gyroscope and magnetic signals from the sensor module as described by Roetenberg *et al.* [22]. The error state  $\mathbf{x}_{\varepsilon,t}$  is expanded with an additional state

$$\mathbf{x}_{\varepsilon,t} = [\mathbf{p}_{\varepsilon,t}, \mathbf{v}_{\varepsilon,t}, \Theta_{\varepsilon,t}, \mathbf{a}_{\varepsilon,t}, \boldsymbol{\omega}_{\varepsilon,t}, \mathbf{q}_{\varepsilon,t}, \Psi_{\varepsilon,t}, \Xi_{\varepsilon,t}]^T. \quad (19)$$

The measurement model becomes

$$\mathbf{C}_t = \begin{bmatrix} \mathbf{I}_3 & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{I}_3 & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{I}_3 & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{I}_3 \end{bmatrix}. \quad (20)$$

The first measurement model would be most obvious, considering both systems have 6 DOF as outputs. The orientation used in the second model is not an independent measurement. It is correlated with the signals of the inertial navigation system. The orientation errors of the magnetic system are relatively high. An error in inclination estimate of 1 degree will result in an acceleration error of  $0.17 \text{ ms}^{-2}$ . This makes it difficult to correct drift errors of the gyroscope. The fusion orientation estimate  $\Xi_t$  appeared to be more accurate than the magnetic orientation estimate  $\Psi_t$ . Therefore, we used both measurements in the implemented system.

- 3) In between magnetic updates, only gyroscopes are used to track orientation changes. At a magnetic update, the orientation measurement will consist of the gyroscope integration, and the weighted sum of the magnetic and fusion orientation

$$\mathbf{C}_t = \begin{bmatrix} \mathbf{I}_3 & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{I}_3 & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{I}_3 & \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{I}_3 & \mathbf{I}_3 \end{bmatrix}. \quad (21)$$

The fusion weights of the measurements are assigned by the values of the covariance matrix  $\mathbf{R}_t$ . The  $\mathbf{R}_t$  parameter is the variance associated with the white measurement noise  $\mathbf{v}_t$ . The noise in one direction is assumed to be uncorrelated with the noise in another direction. Therefore, the nondiagonal elements of the measurement covariance matrix  $\mathbf{R}_t$  matrix are zero.

### III. EXPERIMENTAL METHODS

Three coils were mounted in an orthogonal arrangement as illustrated in Fig. 1 (pyramid: base diameter = 21 cm, height = 11 cm, weight 450 g). Coil dimensions were optimized to minimize approximation errors of a coil compared to a magnetic dipole [19], [23]. The number of windings was 50, the diameter 5.5 cm and the maximum current through the coil 1.5 A. The duration of the magnetic pulses was set at 60 ms, the cycle time ( $T_1$  to  $T_2$ ) was 600 ms. The driving electronics were designed using SMD components to run on 4 AA batteries, making the whole system portable. MTx (Xsens Technologies, The Netherlands) sensor modules were used to measure angular velocities, accelerations, and strengths of magnetic pulses and the earth's magnetic field in 3-D. The size of the MTx sensor module is  $38 \times 53 \times 21 \text{ mm}$  ( $W \times L \times H$ ) and the weight 30 g. The sample frequency of all sensors was 120 Hz with 16-bit resolution using the internal analog-to-digital converter of the sensor module. The sensor modules were connected via a portable data bus system (Xbus Master, Xsens Technologies) providing the sensors with power and transmitting the signals by a wireless Bluetooth connection to a PC (see Fig. 1). A Vicon 470 system (Oxford Metrix, U.K.) consisting of 6 cameras operating at 120 Hz was used as a reference. Three optical markers with a diameter of 25 mm were attached to each sensor module in an orthogonal arrangement to validate the sensor's position and orientation with respect to the position of the coils. One sensor module with markers was attached to the source.

In the first experiments, the set of coils was placed on a table. One sensor was moved by hand near the coils. In this bench-test, distances were varied slowly from approximately 10 cm to 80 cm and the sensor was rotated along all axes. In the following experiments, the three perpendicular coils were attached to the lower back. One sensor was placed on the back of a subject, at the level of the first thoracic vertebra and one sensor was placed on the upper arm, just above the elbow. The subject performed flexion–extension and abduction–adduction of the arm followed by standard anatomical movements of the back: flexion, lateral flexion and rotation. In the final tests, the sensor was placed on the thigh, just above the knee. The subject walked across the laboratory at a comfortable pace for a number of steps. All experiments were repeated 10 times.

### IV. RESULTS

Table I shows the numerical results of all performed experiments. The position error is defined as the distance between the 3-D coordinates from the Kalman filter and the reference coordinates. The orientation error is defined as the smallest angle about which the sensor frame has to be rotated to coincide with the reference frame. Because the orientation estimates of the magnetic system  $\Psi$  were combined with those of the fusion algorithm  $\Xi$ , the orientation accuracy also improved and did not differ much between different movements. They are comparable to the results reported in [21].

Fig. 5 shows the results of an typical experiment where the subject performed flexion and extension of the back three times. In Fig. 5(a), we can see that the orientation of the source  $\Phi$  is changed during the movement. The magnetic source frame can

TABLE I  
RMS POSITION AND ORIENTATION ERRORS AND THEIR STANDARD DEVIATIONS  
OF THE MAGNETIC AND INERTIAL SENSOR FUSION ALGORITHM. ALL  
MOVEMENTS WERE PERFORMED 10 TIMES

Segment	Movement	Position error [mm]		Orientation error [deg]	
		RMS	SD	RMS	SD
Bench-test		5.2	1.1	3.0	0.6
Back (T1)	<i>Flexion</i>	4.8	1.1	2.4	0.5
	<i>Latero-flexion</i>	5.0	0.9	2.6	0.5
	<i>Rotation</i>	4.9	1.0	2.6	0.5
	<i>Walking</i>	5.6	1.8	3.0	0.6
Upper arm	<i>Flexion</i>	5.1	1.3	2.4	0.5
	<i>Abduction</i>	5.0	1.6	2.3	0.5
	<i>Walking</i>	7.9	2.6	3.1	0.6
Thigh	<i>Walking</i>	8.6	2.8	3.2	0.6

be rotated and aligned with the global frame because this orientation is measured. In Fig. 5(b), distance measurements between the source and sensor on the back are plotted for the magnetic and reference system. During flexion, the distance increases a few cm. Fig. 5(c) shows the  $X$ ,  $Y$ , and  $Z$  coordinates of the sensor with respect to the center of the source using the described Kalman filter. From the initial coordinates, we find that the sensor is about 45 cm above the source ( $Z$ -coordinate), 5 cm to right ( $Y$ -coordinate) and 6 cm forward ( $X$ -coordinate). During flexion, the  $X$ -position increases, the  $Z$ -coordinate decreases, while in the  $Y$ -direction, there is hardly any movement. At negative values of the  $Z$ -coordinate, the sensor is positioned lower than the source as can be seen in Fig. 5(a). The root mean square (RMS) position error of this trial is 4.7 mm compared to the optical reference measurements.

Fig. 6 shows a typical example from an experiment where the subject performed abduction and adduction of the arm. In the upper graphs, the distance estimates between the source on the back and the upper arm are plotted which is between 38 and 50 cm. The solid line represents the reference measurement, the stars (\*) are the magnetic updates, and the dotted line is the Kalman fusion of the magnetic and inertial measurements. The middle graph shows the errors of the magnetic system and Kalman filter. The RMS position error of the magnetic system of this trial is 7.2 mm. The RMS error of the Kalman filter is significantly lower with 4.6 mm. In the lower graph, the differences between the orientation obtained with the reference system and the inertial-magnetic measurements are given. The error is the smallest angle about which the sensor frame has to be rotated to coincide with the reference frame and is  $2.1^\circ$  RMS for this trial.

## V. DISCUSSION

In this paper, the combination of magnetic measurements and inertial sensors for fully ambulatory position and orientation tracking is examined. Given the actuator and sensor signals, the magnetic system determines their relative positions and orientations in 6 DOF. This is combined in a Kalman filter to provide actual distance measurements on the body and correct drift errors in estimates of position and orientation changes by the inertial sensors. Experiments were performed with only one subject, but the results show the feasibility of the proposed measurement

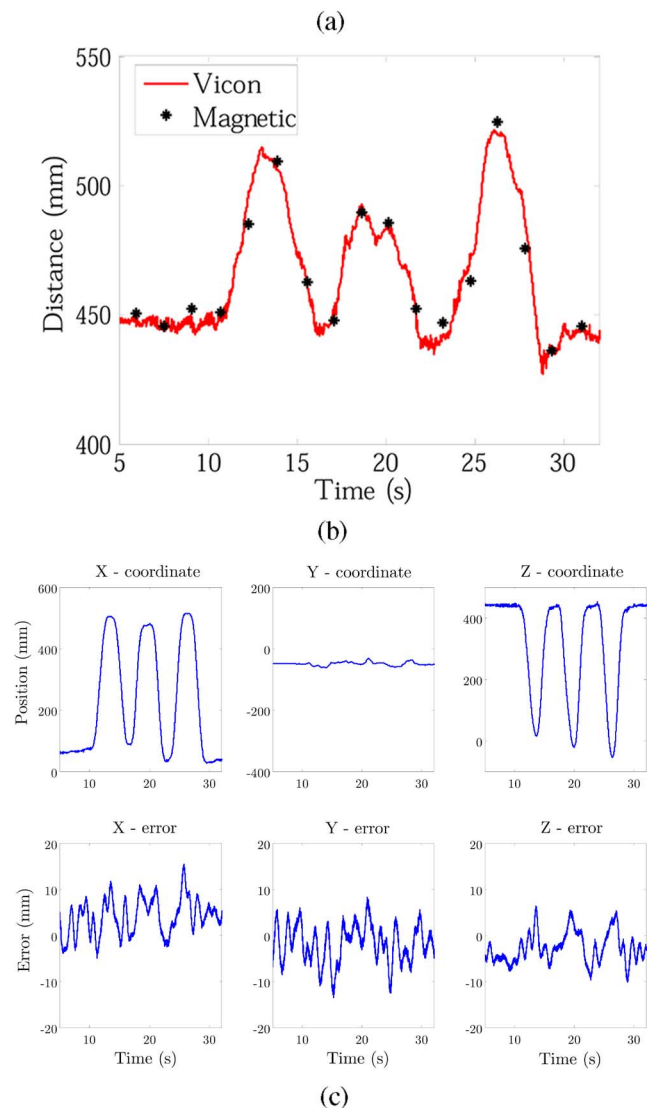
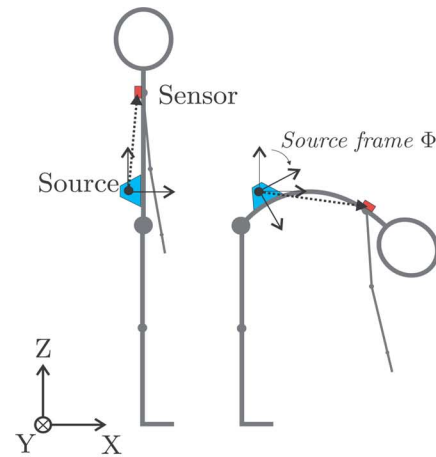


Fig. 5. Experimental results of magnetic and inertial sensor fusion. (a) Position and orientation of the source and sensor change during flexion. (b) Distance between source and sensor. (c) Upper:  $X$ ,  $Y$ , and  $Z$  coordinates of the sensor with respect to the center of the source. The subject performed three times flexion of the back. Lower: Error in coordinates using inertial and magnetic sensing compared with optical references system.

system. A full evaluation with more subjects on a wider range of movements needs to be performed.



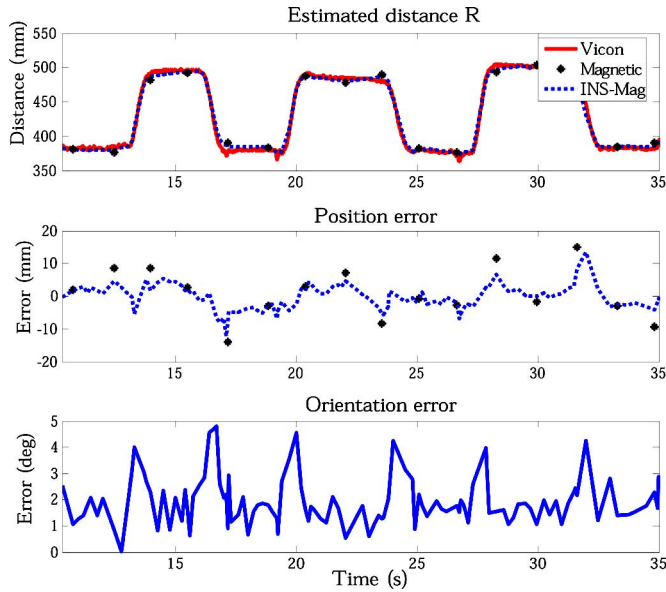


Fig. 6. Magnetic and inertial position and orientation measurements. The upper graph shows the distance between the source on the back and the sensor on the upper arm while performing abduction and adduction of the arm. The solid line represents the reference measurement by Vicon. The magnetic updates are indicated by the stars (\*), and the dotted line is the Kalman fusion of the magnetic and inertial measurements. The middle graph shows the errors of the magnetic system and Kalman filter. The lower graphs show the differences between the orientation obtained with the reference system and the inertial-magnetic measurements.

The relative position output of the system offers valuable information in addition to orientation measurements only. Movements of complex joints such as the shoulder can be reconstructed with all possible DOF. By combining the output with instrumented shoes to measure ground reaction forces proposed by Veltink *et al.* [26], fully ambulatory biomechanical analyses are feasible. The performances do not yet meet requirements of many representative studies, although it may depend on the application. Accuracy and update frequency should be increased to be used in practice. However, there are many points for improvement.

The actuator has a working range of about 70 cm and is placed on the back of a person. This is sufficient to track, for example, shoulder or hip movements. For full ambulatory body tracking, the strength of the emitted field should be enlarged. This can be achieved by increasing the current through the coils or optimizing the coil configuration [23]. Consequently, this will increase the accuracy because of an higher the signal-to-noise ratio of the magnetic tracker. Another solution is to mount multiple sets of (smaller) coils on and around several body parts.

The cycle time of the magnetic updates and current through the coils were fixed. To minimize drift errors, inertial position estimates should be updated at a relatively high rate, however, it will cost more energy. This can be optimized by weighting the accuracy requirements and maximum measurement time with a set of batteries. With the used settings, we were already able to record for about 30 min. Results were obtained in an off-line procedure, however, the system can provide 6 DOF solutions in real-time. In off-line or near real-time analyses, an R.T.S.

smoothing algorithm [8] processing the data also backward in time can be used, reducing errors.

Experiments with relatively slow movements of the arm and back showed significantly lower errors than the experiments where walking was evaluated. The main reason for these higher errors was the relative movement between sensor and source within one cycle of bursts  $B_1$  to  $B_3$  (Fig. 2). In the algorithm for the 6 DOF calculations, the relative position and orientation between source and sensor are assumed to be fixed during one cycle. If these movements are not taken into account, errors are introduced, especially during fast movements. The time  $B_1$  to  $B_3$  can be shortened, but requires some adaptations of the used sensor hardware. The movements of the source and sensor during the cycle of pulsing can be estimated by using the signals of the inertial sensors. The distance between source and sensor can be assessed for each pulse and by triangulation of these distances, the relative position can be obtained. The error as a function of the distance between source and sensor was not taken into account in the Kalman filter model. Incorporating this behavior can also improve the accuracy.

Several studies report effects of nearby conductive and magnetic materials on the accuracy of tracking using magnetic systems [15], [18]. The tracker was tested without metals in the vicinity. It should be investigated how these materials interfere with the emitted magnetic fields. However, since inertial sensors are not affected by magnetic fields, we expect significantly less problems than using magnetic tracking only.

Motion analysis is often combined with recordings of the electric activity of muscles; electromyography (EMG) or other biopotentials. In several studies which recorded EMG together with magnetic motion trackers, e.g., [6] and [17], no influence of magnetic fields on the EMG has been reported. However, possible limitations of using the system jointly with the recording of EMG should be investigated. Loops of electrode wiring should be avoided since the switched magnetic field can cause induced fields distorting the EMG measurements.

This system does not provide the position of a person in, for example, a room. For indoor use, additional magnetic sources or a local positioning system based on a different physical principle can be placed in the measurement volume. An estimate in the horizontal plane with respect to a known starting point can also be made by means of a gait phase detector, a step counter or by processing signals from inertial sensors on the feet [24], [25], [27]. For outdoor applications, a system such as GPS or wireless networks can provide coordinates [10].

In conclusion, there are many possibilities to improve the performance of the proposed system in comparison to the current results which merely present the proof of concept.

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